Ecosystem-based indicators as a tool for mussel culture management strategies

Alejandro Pérez-Camacho[1]; Eva Aguiar[2]; Uxío Labarta*[2]; Vanessa Vinseiro[2]; Mª José Fernández-Reiriz[2]; X. Antón Álvarez-Salgado[2]

[1]IEO – Centro Oceanográfico A Coruña, Muelle de Animas s/n, A Coruña, Spain.

[2]CSIC – Instituto Investigaciones Marinas, Eduardo Cabello 6, E36208 Vigo, Spain.

*Corresponding author; Tel.: +34986231930, Fax: +34986292762, email: labarta@iim.cisc.es

Abstract

The present study seeks to establish industry management strategies based on ecosystem-based indicators in an intensive mussel culture area. Spatial differences in the environmental conditions and in the productivity of mussels cultured on hanging ropes were examined at five locations in Ría de Arousa (NW Spain). The environmental conditions of the ecosystem were described on basis of the next ecosystem-based indicators: hydrography (salinity, temperature and chlorophyll *a*), dynamics (current velocity) and food availability (FA). Mussel productivity was assessed by measuring the biomass per rope, total fresh weight, and length of cultured mussels. Mussel productivity was successfully modelled from empirical relationships with current velocity, chlorophyll *a* and culture density. Commercial production (in kg) was evaluated from biomass and translated into economic value taking into account mussel commercial category. Finally, economic gross yield of each location was related with environmental conditions and culture densities by means of empirical relationships.

Keywords: Mussel production; Ecosystem-based indicators; Food availability; Mussel economic yield; Ría de Arousa (NW Spain).

1. INTRODUCTION

Bivalve culture management is included in ecosystem-based management strategies (Byron et al. 2011) and specifically in the Ecosystem Approach to marine Aquaculture (EAA) (Costa-Pierce, 2008). This ecosystem perspective, seek to find suitable places for mussel farming and to predict potential production, economic outputs and environmental effects. These aspects are essential to minimize environmental impacts and social conflicts (Silva et al. 2011), maximize economic return (GESAM, 2001; Grant et al. 2008), and to ensure sustainable development (Kapetsky and Aguilar-Manjarrez, 2007). This approach inevitably requires the monitoring of environmental variables of the ecosystem. However, insufficient funding is often a limitation in marine ecosystem monitoring (Borja et al., 2013; de Jonge et al., 2006). Therefore, achieving adequate cost-effective monitoring is essential.

The importance of mussel culture in this area (see section 2.1) drove us to establish a mutualism relationship with mussel industries since some time ago through R&D (Research and Development) investment. This type of collaborations seeks to establish relationships between industry and science to discover and create new knowledge about scientific topics for the purpose of uncovering and enabling development of valuable new ecosystem services.

In Galician Rías, the first attempts in achieve an ecosystem perspective were made by Tenore and González (1975) and Tenore at al. (1982) in the rías of Arousa and Muros. Blanton et al. (1987) also showed the first quantitative relationship between upwelling intensity and mussel growth and Pérez-Camacho et al. (1995) demonstrated the influence of seed source, cultivation site and phytoplankton availability for the growth of mussel seed in the Ría de Arousa. Culture density resulted to be another important factor that affects mussel growth in suspended cultures (Cubillo et al. 2012a, 2012b;

Frechétte et al. 1996, 2010; Labarta et al. 2004; Lauzon-Guay et al. 2005, 2006) and that must be regulated by mussel farmers. It is also well-known the substantial variability in growth rates within a single estuary or embayment (Babarro et al. 2003; Dickie et al. 1984; Mallet and Carver 1989; Stirling and Okumus 1994). Site-selection will be therefore another factor of influence in mussel growth that also needs special consideration.

The final aim of this paper is to establish industry management strategies based on ecosystem-based indicators. Results were divided in specific goals: first, the ecological indicators of the ecosystem were described on basis of the hydrography (S, T, Chla), dynamics (current meter records) and food availability (FA) of the five sites under study. Then, mussel productivity parameters (biomass, fresh total weight, and length) were presented for each location. Empirical relationships between the ecosystem indicators and mussel productivity parameters were also reported. Finally, the economic yields of the five rafts and the equations relating them with the ecosystem indicators were also showed.

In our work, nowadays technologies let us to achieve an adequate cost-effective monitoring of environmental variables in five different rafts within a Galician Ría, which is essential for the wanted ecosystem perspective. Moreover, the proximity with mussel farmers let us to obtain real economical values of mussel production depending on the culture density and on the site-selection. The main innovative value of this work is the use of economical commercial values obtained thanks to mussel industry. To the best our knowledge, economical values never were related before with ecological indicators to establish industry management strategies, which was the main aim of this paper.

MATERIALS and METHODS

2.1. Study area

The highest mussel growth rates world-wide have been reported in the four large coastal embayments of NW Spain (Babarro et al. 2000; Fernández-Reiriz et al. 1996; Pérez-Camacho et al. 1995), collectively known as Rías Baixas (Fig. 1a). Mussel production in this area reaches approximately 250,000 tons per year, 40% of the European and 15% of the World production (Labarta et al., 2004). The unique combination of upwelling-favourable winds during the spring and summer (Álvarez-Salgado et al. 2010; Wooster et al. 1976) and coastal morphology make the Rías Baixas exceptional sites for the extensive culture of the blue mussel Mytilus galloprovincialis on hanging ropes.

The Ría de Arousa is the largest of these embayments with an estimated production of 4400 tons of organic carbon in mussel flesh per year, about 10 % of the net primary production of the entire ecosystem (Figueiras et al. 2002). It is located between 42.4º and 42.5º N, with a northeast-southwest orientation, a surface area of 245 km^2, and a volume of 4.34 km^3 (Fig. 1b). This embayment supports a high density of 2404 floating mussel rafts organized into polygons (local term to refer to a farm with tenths of mussel rafts, Fig.1c). There are 24 polygons that occupy 41 km^2, which represents about 17% of the total free surface of the embayment. The surface occupied by rafts in each sector (raft density; area occupied by rafts divided by area of the sector), corresponded to 15.2%, 17.5% and 21.4% of the outer, inner and middle sectors, respectively. Each raft has a size of 20 m x 25 m, supports 500 ropes of 12 m length and it is separated by 100 m from the adjacent rafts. These platforms are anchored with an iron chain at the bow.

2.2. Ecosystem-based indicators

Bivalve production is largely controlled by food availability (Frechétte et al. 1989; Smaal and Van Stralen, 1990), which is determined by phytoplankton concentration

(Fernández-Reiriz et al., 1996; Garen et al., 2004; Page and Hubbard, 1987), and water current velocity (Pérez-Camacho et al. 1995; Strohmeier et al., 2005). Phytoplankton biomass fixes maximum food availability and current velocity in the cultivation area determines the rate at which food is supplied. Some authors reported that temperature and salinity can affect mussel growth (Bayne and Worral, 1980; Brown and Hartwick, 1988a, 1988b; Karayücel and Karayücel, 2000; Nair and Appukuttan, 2003; Seed, 1976). In this work, ecosystem-based indicators were chosen based on the previous bibliography and they were classified into three different groups: (a) dynamics, (b) hydrography and (c) food availability.

(a) Dynamics

ENDECO currentmeters were installed at the bow of five mussel rafts in five polygons of the Ría de Arousa, located at the outer-northern (OuN), middle-northern (MidN), outer-southern (OuS), middle-southern (MidS), and inner-central (InC) sectors of the embayment (Fig. 1b; Table 1). At each site, the current meters were deployed at 1, 6 and 9 m depth. The sampling interval was fixed at 2 min. Velocities were depth-averaged (2-layer circulation was absent through the upper 9 m at all sites) and subsequently time-averaged.

Following Nihoul and Ronday (1975), residual currents are defined as mean currents over a time sufficiently long to cover several tidal periods and thus cancel out most of the tidal contributions. The residual currents are therefore due to other forcings such as winds, river discharges, heat exchange, etc. The duration of the velocity time series used in this manuscript is always longer than 27 days (Table 1). Therefore, we will consider the final values of velocity (depth- and time- averaged) as residual currents from here on.

Tidal currents were characterised applying a harmonic analysis to the raw time series of current velocity using the t_tide code in Matlab® (Pawlowicz et al. 2002).

(b) Hydrography

Vertical profiles of water temperature, salinity, and chlorophyll *a* (Chl*a*) were obtained fortnightly with a Seabird 25 CTD at the 5 rafts; a total of 17 profiles were taken at each site from 7 September 1995 to 10 July 1996. Due to technical problems we have missed data from7 September to 3 October for all sites but the MidS raft. As for the case of the current velocities, depth-averaged (over the upper 9 m) time series of temperature, salinity and Chl*a* were calculated and subsequently, time-averaged for each site.

(c) Food Availability

Food availability (FA) was calculated as:

$$\mathrm{FA} = \frac{[\mathrm{Chl\ a}] \cdot v \cdot A}{N} \tag{1}$$

where [Chl*a*] is the depth-averaged Chl*a* concentration (over the upper 9 m), ν is the depth-averaged water velocity, A is the cross section of each raft [20 m (width of raft) x 12m (length of ropes)], and N is the number of ropes per raft (500). FA values are reported in grams of Chl*a* per hour and rope (g Chl*a* h^{-1} $rope^{-1}$). Obtained FA values were time-averaged for each site.

2.3. Mussel productivity

Mussel productivity was characterised on basis of three parameters: mussel biomass per rope (B), total fresh weight (TFW) and length (L) of each individual mussel. Three culture densities were tested: 400, 500 and 600 mussel m^{-1}.

Forty two culture ropes (12 with 400 mussel m^{-1}, 15 with 500 mussel m^{-1} and 15 with 600 mussel m^{-1}) were planted with collector seeds and kept on the same raft for 3 months prior to the experiment. Then, the ropes were moved to the five commercial rafts indicated in Figure 1b: 9 ropes (3 per culture density) were hung on each raft, except at the InC raft, where 2 culture densities were tested (500 and 600 mussel m^{-1}) and, therefore, only 6 ropes were hung. After 361 days, all ropes were weighted with a digital dynamometer (± 0.1 kg precision). Biomass per rope (B) was estimated using the equation B = PW × 4.966 + 7.011 (R^2 = 0.99; Pérez-Camacho et al. 2013), where PW is the weight of a rope in the water. Ropes were weighed at low tide to eliminate any effect of current drag. Furthermore, 3 ropes and 3 samples (250 mussels) per rope and culture density were collected between 3 and 6 m depth from each raft to determine the total fresh weight (TFW) and the size (L) of mussels. Both dry meat and shell weights (DMW and DSW) were estimated for each case to calculate the condition index according to the equation (Freeman, 1974): CI = (DMW/DSW) x 100.

2.4. Economic yield

At present, the minimum legal commercial size for harvested mussels in Spain is 50 mm. Commercial production (in kg) of each raft was evaluated considering only the biomass of mussels with the legal commercial size. Then, it was translated into economic values (in euro) taking into account the fresh sale commercial categories: small (45–70 pieces kg^{-1}; 0.50 € kg^{-1}), medium (36–45 pieces kg^{-1}; 0.60 € kg^{-1}), large (28–35 pieces kg^{-1}; 0.75 € kg^{-1}), extra-large 2 (21–27 pieces kg^{-1}; 0.90 € kg^{-1}) and extra-large 1 mussels (≤20 pieces kg^{-1}; 1 € kg^{-1}). Economic yields were evaluated using two different methods. In the first one, once removed the non-commercial size mussels, a commercial category was assigned to each rope on basis of the average number of mussels contained in one kg and the economic yield of the rope was calculated considering the previous list of prices of the commercial categories. This method will be named ‘unclassified mussels method’ from here on. The second one is more constrained and was developed with the aim of achieving a higher economic yield. In this case, after removal of the non-commercial size mussels, the mussels on each rope were classified according to their corresponding commercial categories and the economic value was obtained considering the commercial value of each category. This method will be named 'classified mussels method' from here on.

2.5. Data analysis

One-way unbalanced ANOVA were performed to evaluate the differences in environmental parameters between the five locations. Two-way ANOVA were used to assess the effect of the spatial location and the culture density both over mussel productivity and economic yields. One-way ANOVA were made when the interaction between both factors resulted to be not significant; this let us to evaluate the effect of both factors independently.

The hypothesis of normal conditions and homogeneity of variance were demonstrated with the Shapiro-Wilk test ($p>0.05$) and the Levene test ($p>0.05$), respectively. When these conditions were not verified, unbalanced ANOVA's by ranks (equivalent to the Kruskal-Wallis rank test) were used.

As a post-hoc tests to obtain the differences between pairs, Tukey-Kramer test was used with environmental parameters (unbalanced data) and Tukey-HSD (Honestly Significant Difference) test with mussel productivity and economic yield parameters.

Linear regression models were used to explain both the mussel productivity parameters and the economic yield of each raft depending on their culture density and on the environmental parameters (FA, Chl*a*, and current velocity). If the intercept parameter was not significant, it was deleted from the models. In this case, R^2 does not provide the variance explained by the model, so we used the determination coefficient of the measured vs. model-predicted values to calculate it.

Data analysis was performed using the statistical software R 2.15.2 (R Development Core Team, 2011), using the *car* package to make the Levene test and the *lme4* (Bates et al. 2010) and *multcomp* packages to make the Tukey-Kramer test.

3. RESULTS

3.1. Ecosystem-based indicators: dynamics and hydrography of the Ría de Arousa

(a) Dynamics

Velocity roses are presented in Figure 2a. At the OuN raft, the preferential direction of the current was SSW and the intensity was predominantly in the 5–10 cm s^{-1} interval. At the MidN raft, the current direction was NNW-S and the intensity was < 5 cm s^{-1}. For the OuS raft, the primary direction and intensity of the current was ENE-WSW and 5–10 cm s^{-1}, respectively; velocities >10 cm s^{-1} were uncommon. At the MidS raft, the main direction of the current was ESE-WNW. Currents at this confined location were predominantly in the < 5 cm s^{-1} range, lower than at the OuS raft. At the InC raft, the current direction was highly confined along the ENE-SW axis with intensities < 5 cm s^{-1}.

Average residual velocity values at each site are summarised in Table 2a.Velocities were significantly higher in the outer (OuS and OuN) than in the middle part of the ría (MidS and MidN). The velocity recorded at the inner part was not significant different from the rest of locations (Table 2; one-way ANOVA by ranks, $p<0.001$; Tukey-Kramer Test, $p<0.05$).

Tidal ellipses (M_2 component only) are represented in Figure 2b. The magnitude of the tidal component (Table 2a) shows that the highest tidal velocity was produced at OuS and the lowest at MidN. In the northern margin, the orientation of the tidal ellipses was almost perpendicular to the predominant direction of the total current while at the southern margin were almost coincident (Fig. 2a vs. 2b).

(b) Hydrography and food availability

Depth- and time-average values of temperature, salinity, Chl*a*, and food availability were compared among the five sites to characterise the spatial distribution of these key environmental variables within the ría (Table 2b). Average temperatures did not vary among sites (Table 2; one-way ANOVA, $p>0.05$), and exhibited a narrow range between 14.6 and 14.9 ºC. Analogously, the spatial variability in salinity did not exhibit significant differences (Table 2; one-way ANOVA, $p>0.05$). Regarding Chl*a*, in the northern side of the ría (OuN and MidN), concentrations were significantly higher than in the southern side (OuS and MidS). However, Chl*a* at the inner location (InC) was not significantly different from the rest of locations (Table 2; one-way ANOVA by ranks, $p<0.05$; Tukey-Kramer Test, $p<0.05$). Concerning food availability, the value obtained at the OuN raft was significantly higher than in the rest of locations (Table 2; one-way ANOVA, $p<0.05$; Tukey-Kramer Test, $p<0.05$).

3.2. Mussel productivity: biomass, total fresh weight, length and condition index

Table 3 summarises the final biomass (B), length (L), total fresh weight (TFW), and condition index (CI) of cultured mussels for the five rafts and for the three culture densities.

For the B, L and TFW parameters, there was no interaction between the two main factors: culture density and location ($p > 0.05$). Therefore, differences among densities for each raft and differences among rafts for each culture were tested. Significant differences in B were found among the three main culture densities (Appendix I, Table I.1; one-way ANOVA, $p<0.01$; Tukey-HSD test, $p<0.05$): Higher B values corresponded to higher culture densities and vice versa, except at the MidS raft where the biomass obtained at 500 and 600 mussel m^{-1} did not show significant differences. Regarding locations, the highest B values were registered at the OuN raft and the lowest at the MidS raft (Appendix I, Table I.2; one-way ANOVA, $p<0.001$; Tukey-HSD test, $p<0.05$).

For L, there were not significant differences between culture densities (one-way ANOVA, $p>0.05$). Concerning the differences found between locations (Appendix II, Table II.2; one-way ANOVA, $p<0.001$; Tukey-HSD test, $p<0.05$), the highest L were obtained at the OuN raft (86 mm) and the lowest at the MidS raft (76 mm).

TFW only showed significant differences among culture densities (400 and 600 mussel m^{-1}) at the OuN raft, where the weight of mussels was 52 and 46 g, respectively (Appendix III, Table III.1; one-way ANOVA, $p<0.05$; Tukey-HSD test, $p<0.05$). Concerning locations, the heaviest mussels were always observed at the OuN raft and the lightest at the MidS raft (Appendix III, Table III.2; one-way ANOVA, $p<0.01$; Tukey-HSD test, $p<0.05$).

Finally, the lowest condition index (CI) was observed at the MidS raft (~17%) while the highest CI were obtained at the MidN (~25%) and InC (~24%) rafts. Outer areas presented intermediate values of CI (Table 3, two-way ANOVA, $p<0.001$; Tukey-HSD test, $p<0.05$).

3.3. Relationship of mussel productivity with the ecosystem-based indicators and culture density

The productivity parameters (B, TFW, and L; Table 3) were fitted in linear regressions with current velocity (*v*), Chl*a* concentration, FA (Table 2) and culture densities (*d*). Table 4 provides the equations obtained from these fittings. *v*, Chl*a* and *d* together explained 94%, 73% and 71% of the variance of B (Table 4a), of L (Table 4b) and of TFW (Table 4c), respectively, among the five rafts. The fitting using FA rather than *v* and Chl*a* separately reduced the explained variance (92%, 64% and 66%, for B, L and TFW, respectively). For TFW the culture density resulted to be always not significant.

For the individual growth parameters (L and TFW) the culture density resulted to be not significant, however for the B-model the density explained more than the velocity (32% vs. 21%). Moreover, it is remarkable that for the B-model (L- and TFW-models) the Chl*a* explained more (less) variance than the velocity (B-model; Chl*a*: 41% and *v*: 21%, L model; Chl*a*: 27% *v*: 48%, and TFW-model; Chl*a*: 33% and *v*: 42%).

3.4. Economic yield

Two different methods (section 2.4) were used to estimate the economic yield of mussel farming activity under different culture densities and/or environmental conditions. Table 5, shows the commercial production by rope at different densities and at the five locations. The total commercial production per rope (Method 1; Table 5a) was almost the same than the previously reported biomass per rope (Table 3), since almost all the mussels were larger than the commercial size (50 mm). Most of the mussels were within the extra-large 2 commercial category and there were no mussels beneath the large category. The lowest mussel size was at MidS raft. Following method 2 (Table 5b), the extra-large 1 mussels percentage at OuN raft is maximum: 76% (400 mussel m^{-1}), 64%

(500 mussel m^{-1}) and 52% (600 mussel m^{-1}). At MidS, MidN and InC, the maximum percentage is obtained for the extra-large 2 category.

Figure 3, reports the economic value of each raft for the three culture densities, considering the two commercial methods used. There was no interaction between the main factors (culture density and location) for any of the used commercial methods ($p=0.1358$ and $p=0.4438$, method 1 and 2, respectively). Significant differences between the economic sustainability of the rafts were evaluated using one-way ANOVAs (method 1: Appendix IV and method 2: Appendix V). Following method 1, there were significant differences in the economic values of all rafts depending on the culture density (Appendix IV, Table IV.1; one-way ANOVA, $p<0.05$; Tukey-HSD test, $p<0.05$), except at the OuN raft. Higher economic values were obtained at higher densities and vice versa. Regarding locations (Appendix IV, Table IV.2; one-way ANOVA, $p<0.001$; HSD Tukey test, $p<0.05$), the highest economic values were obtained at the OuN raft and the lowest at the MidS raft. Following method 2, significant differences (Appendix V, Table V.1; one-way ANOVA, $p<0.01$; Tukey-HSD test, $p<0.05$) were produced at the OuN, MidN and InC rafts. Concerning locations (Appendix V, Table V.2; one-way ANOVA, $p<0.001$; Tukey-HSD test, $p<0.05$), results are the same than using method 1

3.5. Relationship of the gross economic yield of each raft with the ecosystem-based indicators and culture density

Table 6 provides the equations obtained from fittings among the gross economic yield of each raft and environmental conditions. Results are described only for the second method, since the relationships obtained for both methods were very similar. *v*, Chl*a* and *d* together explained 92% (Table 6b) of the variance of the economic yield. The fitting of the economic yield with FA and *d*, did not change too much the explained variance (90%). In these models, *d* explained a low percentage of variance (19%) compared with the environmental parameters (*v*: 29%, Chl*a*: 46% and FA: 67%).

4. DISCUSSION

The present study characterizes suitable places for mussel farming from an ecosystem perspective. This fact can help mussel farmers to optimize potential production and economic outputs.

4.1. Environmental control of food availability

As a starting point, this work has focused on the factors that control the food availability (FA) in the different cultivation areas of the Ría de Arousa. Chl*a* variability in the ría showed a marked relationship with water circulation. In general, higher Chl*a* values were found in the northern shore of the embayment, producing a FA gradient that increased from the inner to the outer embayment along the northern margin, whereas the southern margin exhibited decreasing values from the outer to the inner reaches of the embayment. Although circulation patterns in the Ría de Arousa are still poorly understood, coastal wind-driven circulation and river discharge are considered their main forcing functions (Otto, 1975; Rosón et al., 1997). Consistently, our data showed that the main entry of shelf waters into the Ría de Arousa is through its southern mouth (OuS). Continental runoff is drained mainly through the northern shore of the ría (Otto, 1975; Rosón et al. 1997) producing a Chl*a* accumulation at the northern margin. Chl*a* might also be favoured by the bathymetry, which is relatively shallow in the northern shore; in fact, several studies suggest increased capacity for plankton retention in areas with specific local topography characteristics (Graham and Largier, 1997; Narváez et al. 2004).

The arrangement of mussel rafts into a mussel farm, the hundreds of ropes on each raft, and the miles of mussels on each rope can modify the local flow (Crandford et al., 2014; Plew, 2011; Stevens et al. 2008; Strohmeier et al. 2005) and, consequently, the food availability. This fact was pointed out in our study: maximum and minimum velocity values were reached in sparsely (external area: 15.2%) and densely (central area: 21.4 %) occupied areas, respectively. The optimal intra-raft velocity -to increase the mussel consumption rate- is unclear. Newell (2005) proposed that it was between 2–8 cm s^{-1}. Widdows et al. (2002) established upper and lower limits of 5 and 80 cm s^{-1} and Wildish and Miyares (1990) reported a reduction in *M. edulis* feeding rates with increased current velocities between 5 and 30 cm s^{-1}. In the present study, velocities at the five sites (measured in the bow of each raft) were consistent with these optimal values.

4.2. Environmental control of mussel productivity

The high FA described at the outer northern site was consistent with the highest growth rates recorded in this area. FA also explained the intermediate growth rates observed at the OuS, MidN, and InC rafts, and the lower growth rates at the MidS raft. Babarro et al. (2003), Dickie et al. (1984), Mallet and Carver (1989) and Stirling and Okumus (1994) also established that the location was the primary factor affecting mussel growth. Pérez-Camacho et al. (1995) also found growth differences in *M. galloprovincialis* depending on raft location in the Ría de Arousa.

Some authors reported that temperature and salinity can affect mussel growth (Bayne and Worral, 1980; Karayücel and Karayücel, 2010; Nair and Appukuttan, 2003), however, in our results, temperature and salinity were not relevant for explaining the observed differences in mussel production.

Some studies have reported that mussel energy acquisition is a function of phytoplankton concentration and current speed (Frechétte et al. 1989; Smaal and Van Stralen, 1990). In our study area, Chl*a* concentration and current velocity resulted to be the determining factors of mussel productivity in terms of B, L or TFW.

Despite that cultivation density have important effects on mussel growth (Cubillo et al. 2012a, 2012b; Frechétte et al. 1996, 2010; Labarta et al. 2004; Lauzon-Guay et al. 2005, 2006), in our study, it impacted significantly on biomass, but not on the individual parameters L and TFW. This fact is result of the high food availability at this Ría.

In the B-model, Chl*a* is the most important factor, contrarily to the L and TFW-models, where the velocity achieves a higher importance in the individual growth of mussels. Filgueira et al., 2014, also observed that mussel's length and total fresh weight were good sensitive indicators of the ecosystem status. Our results confirmed previous studies that examined the relationship between growth and environmental factors (Frechétte et al. 1989; Page and Hubbard, 1987; Pérez-Camacho et al. 1995) but in our work, we have taken into account other issues. We have used a higher spatial resolution (5 rafts) than in the previous studies, we have included the culture density as a new variable and, finally, we have considered three different indices of mussel productivity: the individual mussel growth parameters (L and TFW) and the total production of rafts (B). These considerations let us to be more precise in our results and in the economic yield estimations.

4.3. Environmental control of economic yield of rafts

Gross economic yields of rafts depend on the existing commercial categories. In the beginnings of mussel culture, only three commercial sizes were considered and the minimal commercial size was 70 mm. Nowadays, there are five commercial sizes and the minimal has decrease until 50 mm (Pérez-Camacho et al. 2013). These considerations are not only due to market demands but also to a physiological and ecological mussel culture approach (Pérez-Camacho et al. 2000) and, especially, to a viable and sustainable commercial production.

Commercial production results show that to improve the economic yield of rafts, the culture density of ropes must be adjusted depending on the cultivation area. The economic yields of the northern rafts and the inner one resulted to be depended of the culture density, while at southern rafts this dependency was accomplished only between the extreme values of the density (400 and 600 mussel m^{-1}). Our results indicate that it is strongly recommended to use at least the density of 600 mussel m^{-1} in all the rafts, using an initial size around 50 mm. However, previous studies confirm that higher densities can produce higher yields (Cubillo et al., 2012b; Fuentes-Santos et al., 2013). If is needed a lower culture density (500 mussel m^{-1}), the MidS raft is where the economic loss would be less. It is coherent with the low food availability of this area.

There are also large differences in the economic yields depending on the location of rafts. At the OuN (MidS) raft the economic yield is significantly higher (lower) than at the rest of rafts. This difference is related with ecosystem indicators according to the relationships obtained in Table 6b. These models show that ecosystem indicators have to be considered as key factors to determine the economic yield of a raft. Ecosystem indicators will let mussel farmers to choose the appropriate site-selection and culture density, according with their priorities.

5. CONCLUSIONS

Mussel culture management strategies based on ecosystem-based indicators were developed in this work. The different economic yields obtained in each raft were highly related with environmental conditions and therefore with its location. Therefore, site-selection resulted to be of a great importance in the industry management strategies: rafts placed at the northern shore of the Ría were more profitable than the ones placed at the southern shore. Culture density also must be taking into account by mussel industry in the study area. Our results suggest that higher yields are obtained using higher densities. We think that the high carrying capacity of the study area may be related with this fact. However, further development of this stream of research pass by the use of a broader spectrum of culture densities in order to get the optimal culture density.

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Figure captions

Figure 1 Study area. (a) Position of the Ría de Arousa within the costal upwelling system of the Rías Baixas (Vigo, Pontevedra, Arousa and Muros-Noia). (b) Ría de Arousa: position of the sampled rafts, OuS (Outer South), MidS (Middle South), OuN (Outer North), MidN. (c) Mussel rafts inside the Ría de Arousa: Inner part (52.5 km^2, 3 polygons, 17.5% occupied by rafts); Middle part (97 km^2, 15 polygons, 21.4% occupied by rafts) and Outer part (60km^2, 6 polygons, 15.2% occupied by rafts). The number associated to each polygon corresponds to the number of rafts inside it. (Middle North), InC (Inner Center)

Figure 2 (a) Depth-averaged raw velocity and (b) tidal ellipse of the main tidal component (M_2) at the five rafts.

Figure 3 Estimation of the gross economical yield of each raft (euros) depending on the culture density. Two estimation methods were used: ‘unclassified mussels (black) and ‘classified mussels (gray).

Figure 1

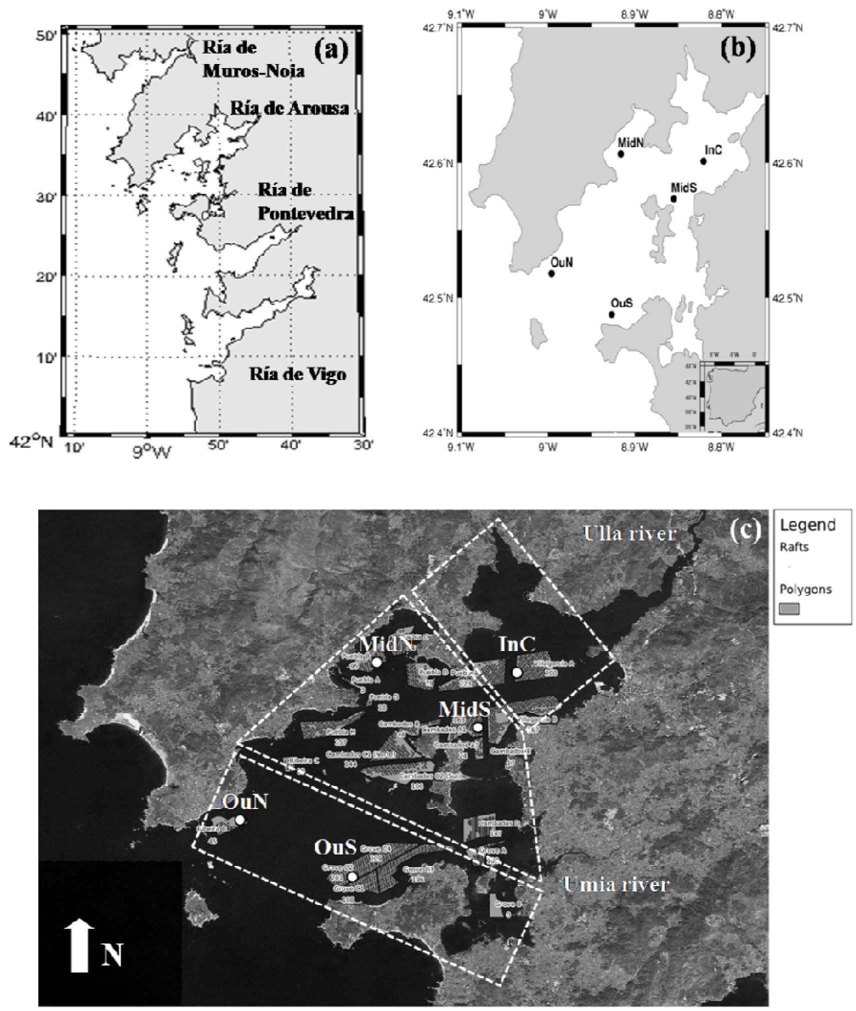
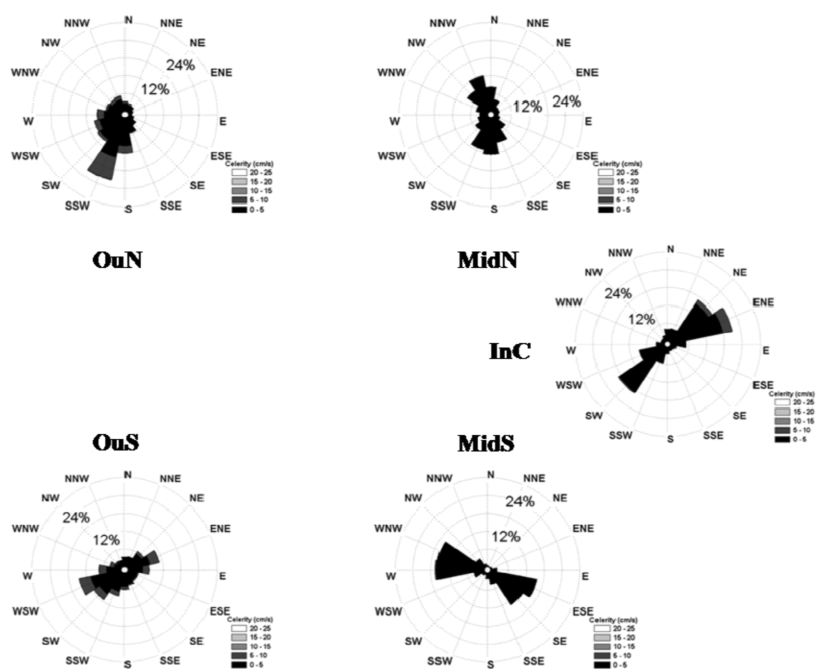

(a)
Ría de
Muros-Noia
Ría de Arousa
Ría de
Pontevedra
Ría de Vigo
50'
40'
30'
20'
10'
42°N
10'
9°W
50'
40'
30'
(b)
9.1°W
9°W
8.9°W
8.8°W
42.7°N
42.6°N
42.5°N
42.4°N
MidN
InC
MidS
OuN
OuS
(c)
Ulla river
Umia river
MidN
InC
MidS
OuN
OuS
N
Legend
Rafts
Polygons

Figure 2

(a)


N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
12%
24%
Celerity (cm/s)
20 - 25
15 - 20
10 - 15
5 - 10
0 - 5
OuN
MidN
InC
OuS
MidS

(b)

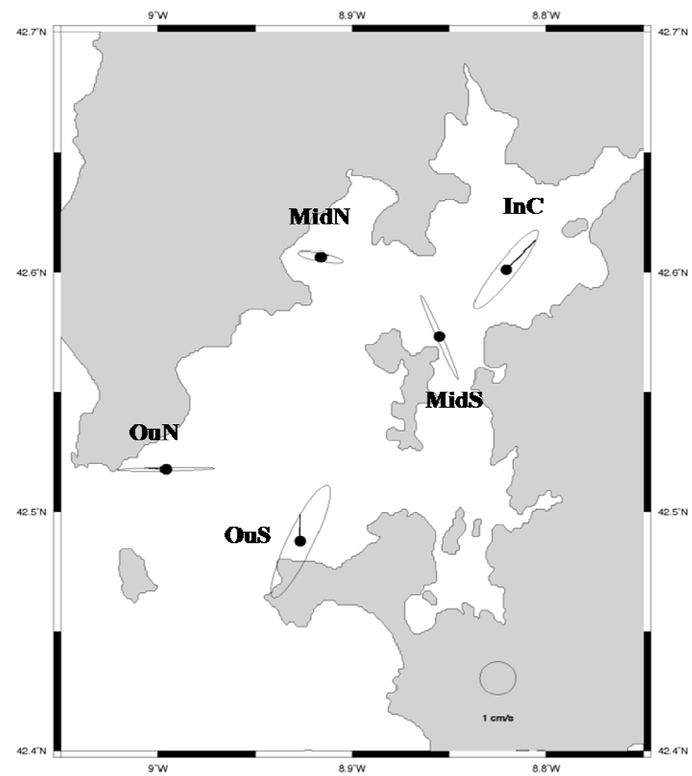
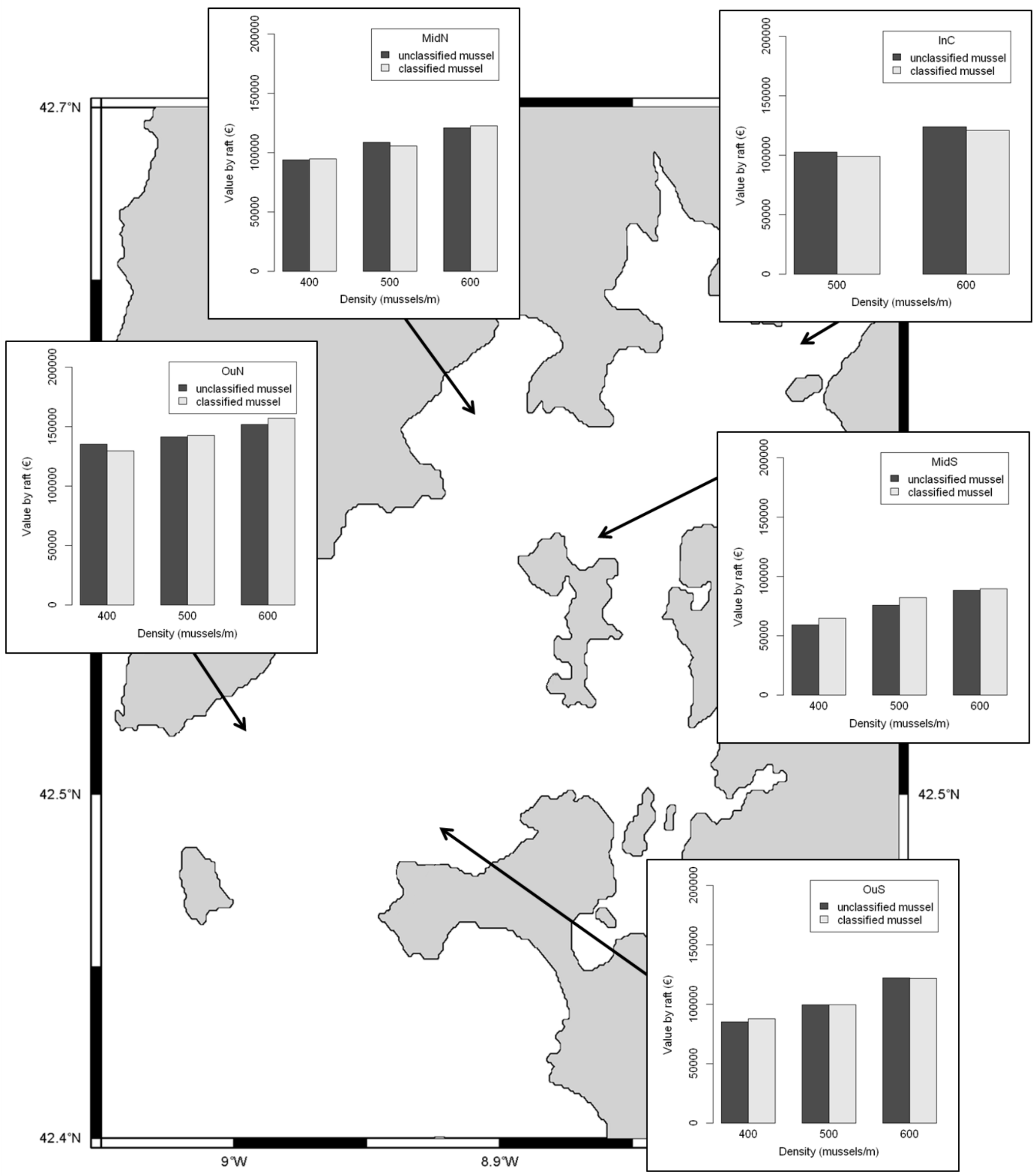

9°W
8.9°W
8.8°W
42.7°N
42.6°N
42.5°N
42.4°N
MidN
InC
MidS
OuN
OuS
1 cm/s

Figure 3


MidN
unclassified mussel
classified mussel
Value by raft (€)
Density (mussels/m)
InC
OuN
MidS
OuS
42.7°N
42.5°N
42.4°N
9°W
8.9°W

List of Tables

Table 1 Currentmeter time series: position of the five rafts in the Ría de Arousa (latitude, longitude), sampled depths, number of data (n) and maximum depth of each location (max. depth).

Locations	Latitude	Longitude	Depths	n	Max. depth
OuS	42º29.2535'	–8º 55.5978'	3–6–9	35359	35
MidS	42º34.3811'	–8º51.3015'	3–6	20765	25
OuN	42º31.0748'	–8º59.7593'	3–6–9	18496	25
MidN	42º36.3798'	–8º54.9686'	3–6–9	25908	20
InC	42º36.0640'	–8º49.2401'	3–6–9	20198	20

Table 2 (a) Dynamics: Depth- and time-averaged values of residual velocity (v; cm s^{-1}) and of the M_2 tidal component (M_2; cm s^{-1}) at each location. (b) Hydrography: Depth- and time-averaged values of salinity (S; psu), temperature (T; ºC) and Chl*a* content (Chl*a;* mg m^{-3}). (c) Food availability (FA; g Chl*a* h^{-1} $rope^{-1}$) at the five locations in the Ría de Arousa*. Superscripts show the statistically significant homogeneous groups among the five locations (Tukey-Kramer, $p<0.05$).***** mean ± standard deviation

	(a) Dynamics		**(b) Hydrography**			**(c) FA**
	v	**M_2**	**S**	**T**	**Chl*a***	
OuS	4.1 ± 2.0^{a}	2.5 ± 1.0	35.0 ± 0.7^{a}	14.7 ± 0.9^{a}	1.5 ± 0.9^{b}	0.1 ± 0.1^{b}
MidS	2.0 ± 1.4^{b}	1.7 ± 0.8	34.4 ± 1.5^{a}	14.7 ± 0.8^{a}	1.8 ± 0.9^{b}	0.1 ± 0.1^{b}
OuN	4.0 ± 2.1^{a}	1.7 ± 0.8	34.2 ± 1.2^{a}	14.9 ± 1.1^{a}	3.1 ± 1.8^{a}	0.3 ± 0.2^{a}
MidN	2.0 ± 1.1^{b}	0.8 ± 0.3	33.9 ± 1.4^{a}	14.8 ± 0.9^{a}	2.5 ± 1.0^{a}	0.1 ± 0.1^{b}
InC	3.0 ± 1.6^{ab}	1.9 ± 0.8	34.0 ± 1.6^{a}	14.6 ± 0.7^{a}	2.0 ± 1.0^{ab}	0.1 ± 0.1^{b}

Table 3 Biomass (B), length (L), total fresh weight (TFW) and condition index (CI) after 361 daysat the five mussel rafts in the Ría de Arousa. *Superscripts show the statistically significant homogeneous groups among the five locations and culture densities (two-way ANOVA, $p<0.001$; Tukey-HSD Test, $p<0.05$).

	B (kg rope^{-1})	**L (mm)**	**TFW (g)**	**CI (%)**
OuS				
400 mussel m^{-1}	189.3 ± 1.5	83.79 ± 0.51	44.62 ± 2.31	22.47 ± 0.01^{ef}
500 mussel m^{-1}	221.3 ± 6.0	83.50 ± 0.69	42.26 ± 3.85	20.99 ± 0.09^{d}
600 mussel m^{-1}	271.2 ± 21.1	81.10 ± 2.32	41.65 ± 3.95	22.06 ± 0.37^{e}
MidS				
400 mussel m^{-1}	157.2 ± 11.3	76.66 ± 1.15	34.75 ± 0.93	19.11 ± 0.14^{c}
500 mussel m^{-1}	201.2 ± 4.6	75.74 ± 1.15	34.38 ± 1.48	16.62 ± 0.17^{a}
600 mussel m^{-1}	219.8 ± 11.2	75.11 ± 1.43	34.11 ± 2.83	17.63 ± 0.29^{b}
OuN				
400 mussel m^{-1}	270.3 ± 8.6	86.96 ± 0.85	52.19 ± 1.02	22.45 ± 0.01^{ef}
500 mussel m^{-1}	302.5 ± 3.8	85.38 ± 3.40	47.85 ± 3.35	21.20 ± 0.41^{d}
600 mussel m^{-1}	336.8 ± 9.4	84.72 ± 0.69	45.78 ± 1.40	22.62 ± 0.09^{ef}
MidN				
400 mussel m^{-1}	208.5 ± 6.1	81.99 ± 0.72	42.40 ± 1.40	24.87 ± 0.11^{g}
500 mussel m^{-1}	241.0 ± 1.0	80.89 ± 1.06	39.91 ± 2.91	22.88 ± 0.15^{f}
600 mussel m^{-1}	268.2 ± 7.0	81.68 ± 0.43	43.16 ± 1.33	24.91 ± 0.09^{g}
InC				
500 mussel m^{-1}	227.6 ± 7.3	78.99 ± 1.72	38.98 ± 2.44	24.35 ± 0.33^{g}
600 mussel m^{-1}	275.7 ± 13.3	79.18 ± 0.66	39.45 ± 1.98	22.63 ± 0.10^{ef}

Table 4 Empirical relations between mussel productivity parameters, culture density (d, mussel m^{-1}) and environmental conditions. Growth parameters are defined from biomass (B; kg $rope^{-1}$; Table 4a), length (L; mm; Table 4b) and total fresh weight (TFW; g; Table 4c), environmental conditions are characterized from food availability (FA; g Chl*a* h^{-1} $rope^{-1}$), velocity (v; cm s^{-1}) and/or Chl*a* (Chl*a*; mg m^{-3}).

	Estimated coefficients	Std. Error	Pr(>t)	Standardized Coefficients	$R^2_{Adjusted}$	Explained Variance
(a) Biomass						
B = 0.32d+529FA						
d	0.32	0.01	<0.001	0.60		
FA	529	29	<0.001	0.77	0.99	0.92
B = –107+0.35d+20ν+49Chl*a*						
Intercept	–107	14	<0.001			
D	0.35	0.02	<0.001	0.60		
N	20	2	<0.001	0.40		
Chl*a*	49	3	<0.001	0.62	0.94	0.94
B = 0.47d						
d	0.47	0.01	<0.001	0.58	0.97	0.32
B = 164+530FA						
Intercept	164	12	<0.001			
FA	530	73	<0.001	0.75	0.56	0.56
B = 170+24ν						
Intercept	170	22	<0.001			
ν	24	7	<0.01	0.48	0.21	0.21
B = 129+51Chl*a*						
Intercept	129	22	<0.001			
Chl*a*	51	9	<0.001	0.65	0.41	0.41
(b) Length						
L = 79–0.01d+43FA						
Intercept	79	2	<0.001			
d	–0.01	0.00	<0.05	–0.19		
FA	43	5	<0.001	0.78	0.63	0.64
L = 72–0.01d+2.6ν+2.8Chl*a*						
Intercept	72	2	<0.001			
d	–0.01	0.00	<0.05	–0.19		
ν	2.6	0.3	<0.001	0.65		
Chl*a*	2.8	0.5	<0.001	0.45	0.71	0.73
L = 86–0.01d						
Intercept	86	4	<0.001			
d	–0.01	0.01	0.18	–0.21	0.02	0.02
L = 74.8+43FA						
Intercept	74.8	0.9	<0.001			
FA	43	5	<0.001	0.78	0.60	0.60

L = 73+2.8ν						
Intercept	73	1	<0.001			
ν	2.8	0.5	<0.001	0.70	0.48	0.48
L = 74+3.3Chl*a*						
Intercept	74	2	<0.001			
Chl*a*	3.3	0.8	<0.001	0.53	0.27	0.27
(c) Total Fresh Weight						
TFW = 38–0.01d+64FA						
Intercept	38	3	<0.001			
d	–0.01	0.01	0.07	–0.17		
FA	64	7	<0.001	0.80	0.65	0.66
TFW = 27–0.01d+3.4ν+4.6Chl*a*						
Intercept	27	4	<0.001			
d	–0.01	0.01	0.06	–0.17		
ν	3.4	0.5	<0.001	0.59		
Chl*a*	4.6	0.8	<0.001	0.51	0.70	0.71
TFW = 48–0.01d						
Intercept	48	5	<0.001			
d	–0.01	0.01	0.23	–0.19	0.01	0.01
TFW = 32+64FA						
Intercept	32	1	<0.001			
FA	64	8	<0.001	0.80	0.63	0.63
TFW = 30+3.8ν						
Intercept	30	2	<0.001			
ν	3.8	0.7	<0.001	0.66	0.42	0.42
TFW = 30+5Chl*a*						
Intercept	30	3	<0.001			
Chl*a*	5	1	<0.001	0.59	0.33	0.33

Table 5 Commercial production per rope for each culture density at the five rafts: (a) Method 1 (*unclassified mussels*): total commercial production by rope (*Kg*), pieces kg^{-1}: number of mussels contained in one kilogram and commercial categories following the corresponded commercial size-classification (section 2.4); (b) Method 2 (*classified mussels*): commercial production in each rope (kg), according to the commercial size-classification.

(a) Method 1: Unclassified mussels				**(b) Method 2: Classified mussels**					
	Total Production by rope (kg)	**Pieces kg^{-1}**	**Commercial Category**		**Production small (kg)**	**Production medium (kg)**	**Production large (kg)**	**Production extra large 2 (kg)**	**Production extra large 1 (kg)**
OuS				*OuS*					
400	189 ± 1	22	Extra large 2	**400**	1.7 ± 0.6	4± 3	16 ± 3	77 ± 14	90 ± 16
500	221 ± 6	24	Extra large 2	**500**	3 ± 2	6± 6	38 ± 17	90 ± 14	84 ± 38
600	271 ± 21	24	Extra large 2	**600**	3 ± 1	14± 9	35 ± 10	115 ± 29	103 ± 52
MidS				*MidS*					
400	157 ± 11	29	Large	**400**	7 ± 2	18 ± 5	40 ± 12	75 ± 17	18 ± 2
500	201 ± 5	29	Large	**500**	8 ± 4	22 ± 9	65 ± 4	84 ± 10	22 ± 10
600	220 ± 11	29	Large	**600**	10 ± 7	25 ± 5	63 ± 9	98 ± 21	23 ± 20
OuN				*OuN*					
400	270 ± 9	19	Extra large 1	**400**	2.1 ± 0.8	8 ± 4	10 ± 6	47± 20	204± 15
500	302 ± 4	21	Extra large 1	**500**	3 ± 2	8 ± 7	20± 9	79± 18	192± 33
600	337 ± 9	22	Extra large 2	**600**	6 ± 2	6 ± 1	21± 5	128± 18	175± 18
MidN				*MidN*					
400	208 ± 6	24	Extra large 2	**400**	1.6 ± 0.7	7 ± 1	27 ± 9	92± 9	81± 8
500	241.0 ± 0.1	25	Extra large 2	**500**	2 ± 1	7 ± 5	62 ± 33	105± 29	65± 19
600	268 ± 7	23	Extra large 2	**600**	1.0 ± 0.1	6 ± 4	31 ± 4	123± 12	107± 12
InC				*InC*					
500	227 ± 7	25	Extra large 2	**500**	3 ± 2	15 ± 6	43 ± 14	109 ± 9	57 ± 20
600	275 ± 13	25	Extra large 2	**600**	6 ± 3	16 ± 6	54 ± 18	115 ± 20	84 ± 20

Table 6 Empirical relations between the gross economic yield of each raft (in euros), culture density (d, mussel m^{-1}) and environmental conditions. Gross economic yield is estimated from biomass per rope using two different methods: (a) Method 1 (*unclassified mussels*) and (b) Method 2 (*classified mussels*). Environmental conditions are characterized from food availability (FA; g Chl*a* h^{-1} $rope^{-1}$), velocity (v; cm s^{-1}) and/or Chl*a* (Chl*a*; mg m^{-3}).

		Estimated coefficients	Std. error	Pr(>t)	Standardized coefficients	$R^2_{Adjusted}$	Variance explained
(a) Economic yield (unclassified)							
Yield = 123d+309400FA							
	d	123	7	<0.001	0.45		
	FA	309400	211	<0.001	0.83	0.99	0.86
Yield =–68606+148d+13365ν+27514Chl*a*							
	Intercept	–68606	10859	<0.001			
	d	148	17	<0.001	0.46		
	ν	13365	1463	<0.001	0.48		
	Chl*a*	27514	2290	<0.001	0.63	0.89	0.89
Yield = 210d							
	d	210	7	<0.001	0.43	0.95	0.17
Yield = 61129+315839FA							
	Intercept	61129	5719	<0.001			
	FA	315839	35392	<0.001	0.82	0.66	0.66
Yield = 60844+15497ν							
	Intercept	60844	11511	<0.001			
	ν	15497	3646	<0.001	0.56	0.29	0.29
Yield = 42378+29485Chl*a*							
	Intercept	42378	11566	<0.001			
	Chl*a*	29485	5049	<0.001	0.68	0.45	0.45
(b) Economic yield (classified)							
Yield = 127d+299000FA							
	d	127	5	<0.001	0.48		
	FA	299000	17450	<0.001	0.83	0.99	0.90
Yield = –64423+149d+12545ν+26812Chl*a*							
	Intercept	–64423	8725	<0.001			
	d	149	14	<0.001	0.48		
	ν	12545	1176	<0.001	0.47		
	Chl*a*	26812	1840	<0.001	0.65	0.92	0.92
Yield = 212d							
	d	212	7	<0.001	0.46	0.96	0.19
Yield = 63513+303977FA							
	Intercept	63513	5378	<0.001			
	FA	303977	33277	<0.001	0.82	0.67	0.67
Yield = 64128+14621ν							
	Intercept	64128	11054	<0.001			
	ν	14621	3501	<0.001	0.55	0.29	0.29
Yield = 44933+28618Chl*a*							
	Intercept	44933	10891	<0.001			
	Chl*a*	28618	4754	<0.001	0.69	0.46	0.46

APPENDIX A: Biomass (B, Kg rope^{-1})

Table I.1 Comparison of the biomass depending on the cultured density: one-way ANOVA, $p<0.01$; Tukey-HSD test, $p<0.05$

Culture density (mussel m^{-1})	OuS	Homog. groups	MidS	Homog. groups	OuN	Homog. groups	MidN	Homog. groups	InC	Homog. groups
400	189.3	A	157.2	A	270.3	A	208.5	A	–	
500	221.3	B	201.2	B	302.5	B	241.0	B	227.6	A
600	271.2	C	219.8	B	336.8	C	268.2	C	275.7	B

Table I.2 Comparison of the biomass between locations: one-way ANOVA, $p<0.001$; Tukey-HSD test, $p<0.05$

Location	400 mussel m^{-1}	Homog. Groups	500 mussel m^{-1}	Homog. Groups	600 mussel m^{-1}	Homog. groups
OuS	189.3	B	221.3	B	271.2	B
MidS	157.2	A	201.2	A	219.8	A
OuN	270.3	C	302.5	D	336.8	C
MidN	208.5	B	241.0	C	268.2	B
InC	–		227.6	B	275.7	B

APPENDIX B: Length (L, mm)

Table II.1 Comparison of the mussel length depending on the cultured density: no significant differences were found

Table II.2 Comparison of the mussel length between locations: one-way ANOVA, $p<0.001$; Tukey-HSD test, $p<0.05$; whatever to be the density.

Location	L (mm.)	Homog. groups			
OuS	82.80			C	
MidS	75.84	A			
OuN	85.69	D			
MidN	81.52			C	
InC	79.08		B		

APPENDIX C: Total Fresh Weight (TFW, Kg)

Table III.1 Comparison of the mussels TFW depending on the cultured density: differences in the TFW between cultured densities were only significant at OuN location (one-way ANOVA, $p<0.05$; Tukey-HSD test, $p<0.05$).

Culture density (mussel m^{-1})	OuN	Homog. groups
400	52.19	B
500	47.85	A B
600	45.78	A

Table III.2 Comparison of the mussels TFW between locations: one-way ANOVA, $p<0.01$; Tukey-HSD test, $p<0.05$.

Location	400 mussels m^{-1}	Homog. groups	500 mussels m^{-1}	Homog. groups	600 mussels m^{-1}	Homog. groups
OuS	44.62	B	42.26	B C	41.65	B
MidS	34.75	A	34.38	A	34.11	A
OuN	52.19	C	47.85	C	45.78	B
MidN	42.40	B	39.91	A B	43.16	B
InC	–		38.98	A B	39.45	A B

APPENDIX D: ECONOMIC VALUES OF RAFTS (Euros; €); Method 1: unclassified mussels

Table IV.1 Comparison of the economical values depending on the cultured density: one-way ANOVA, $p<0.05$; Tukey-HSD test, $p<0.05$.

Culturedensity (mussel m^{-1})	OuS	Homog. groups	MidS	Homog. groups	MidN	Homog. groups	InC	Homog. groups
400	85200	A	58937	A	93825	A	–	
500	99585	B	75414	A B	108465	B	102299	A
600	122025	C	88087	B	120705	C	123942	B

Table IV.2 Comparison of the economical values between locations: one-way ANOVA, $p<0.001$; Tukey-HSD test, $p<0.05$.

Location	400 mussel m^{-1}	Homog. groups	500 mussel m^{-1}	Homog. groups	600 mussel m^{-1}	Homog. groups
OuS	85200	B	99585	B	122025	B
MidS	58937	A	75414	A	88087	A
OuN	135150	C	141232	C	151560	C
MidN	93825	B	108465	B	120705	B
InC	–		102299	B	123942	B